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<u>Progress Report</u>

High Frequency Behavior of Long and Small Junctions

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Abstract

Results are presented of studies on long Josephson junctions and on very small junctions. The long junctions were made out of NbN. Experiments were made on the lifetimes of fluxon states from 2 K to 0.01 K; they are of importance to a fundamental understanding of tunneling and nucleation. Multi-fluxon resonances were observed and they are of interest to the application of long junctions as high frequency oscillators. Very small junctions, all NbN, were fabricated using a STM approach. Results show the Coulomb blockade, the Coulomb staircase, and the superconducting energy gap. The two types of junctions are being combined to observe Bloch oscillations.

1. INTRODUCTION

The goals of this project are:

- to study the dynamics of fluxons in long Josephson junctions and related fundamental effects.
- to study the characteristics of fluxon oscillators.
- to apply the fluxon oscillator to the study of single electron tunneling in very small junctions.

This project deals with two extreme situations in junctions: Josephson junctions long enough to contain fluxons (one dimension L of the junction is greater than the Josephson penetration depth, $L > \lambda_J$), and tunnel junctions so small that the electrostatic energy dominates their behavior when the thermal energy kT is reduced to the point it does not mask the effects. The two types of junctions are difficult to fabricate because:

- when the junction is long there is a greater probability of defects and shorts
- when it is very small (much less than 0.1 μm × 0.1 μm) it is difficult to control in the fabrication such small dimensions

To observe single electron tunneling characteristics the following conditions have to be satisfied:

(i) electrostatic energy dominates, such that

$$\frac{e^2}{2C} > kT \tag{1}$$

where C is the capacitance of the junction and e the charge of 1 electron.

(ii) The junction resistance R should be greater than $h/4e^2$ to avoid lifetime broadening effects.

When these conditions are met the tunneling process is no longer stochastic in nature. This was shown by Zeller and Giaever[1] in 1969 and recently it has received considerable theoretical interest[2] based on quantum mechanical calculations. No tunneling is possible at low voltages and hence the junction exhibits very low conductance. However, at a voltage $V = e/2C$ the electrons tunnel, one at a time[3]. This is called the Coulomb blockade.

Because in such a junction, current-biased, the electrons are expected to tunnel one at a time at more or less fixed time intervals, such single-electron tunneling gives rise to coherent voltage oscillations with a frequency f,

$$f = I/e \qquad (2)$$

This is interesting because charges move into the junction <u>continuously</u> but a charge transfer across the junction occurs in <u>discrete</u> steps. The reason for these oscillations is that in a current-biased junction, an electron sees a periodic potential as one electron moves in and others come in. When the junction is superconducting, voltage oscillations are expected at

$$f = I/2e \qquad (3)$$

Such oscillations are referred to as Bloch oscillations while SET (single electron tunneling) oscillations are for single electrons. They have never been observed directly. The oscillations are called Bloch type because a similar effect has been predicted for regular solids: when a constant electric field is applied to electrons in a periodic potential, reflections should cause oscillations. However, because of inelastic scattering and incoherent motion of the many electrons, these oscillations have not been seen. In small junctions the electron behavior is expected to be coherent and hence the effect should be seen. It is a dynamic effect.

To investigate this, we have taken an approach which consists of:

- satisfying equation 1, by fabricating a very small junction and going to very low temperatures. For the moment, a small junction was fabricated by using a STM (Scanning Tunneling Microscope) device.

- measuring the Bloch/SET (Single Electron Tunneling) oscillations by beating against them with an external microwave source. It is more convenient to use a local source of microwaves, a long Josephson junction oscillator coupled to the small junction. Of course it is always possible to try to detect the emission of the coherent radiation (in the microwave region) from the very small junction. A beating technique makes it much easier to detect. For a given frequency from the external oscillator, there should be regularly spaced spikes in the I-V characteristics corresponding to the value of the dc current where the Bloch oscillations are in step with the applied radiation.

Because this research deals with both aspects of the problem, the generation of coherent radiation and its detection, results will be presented on fundamental aspects of long Josephson junctions, and on the behavior of very small junctions.

2. RESULTS

A. Tunneling in Long Josephson Junctions

Long Josephson junctions were fabricated in a magnetron sputtering system. They had the following characteristics:

- top electrode, NbN, 3000 Å thick
- barrier, MgO, ~20 Å thick
- bottom electrode, NbN, 3000 Å thick.

The junction dimensions were 100 μm long, 6 μm wide. Current densities were in the range of 100 A/cm^2 to 1,000 A/cm^2.

In an external magnetic field, a long Josephson junction shows current steps at fixed voltages in the I-V characteristics. These are known as Fiske steps and they correspond to the resonant motion of fluxons in the junction which behaves as a cavity. The coupling of the fluxon motion to the discrete cavity modes causes the resonances. By varying the external magnetic field, the

coupling to specific modes can be changed; the magnetic field modifies the spatial distribution of the current within the junction.

The Fiske steps, interesting by themselves, constitute a series of well-defined energy levels. In essence, a fluxon or a plasma wave produced by the fluxon can be in these energy levels. A question of current interest is related to the ability of fluxons (or plasma waves) to change energy states by thermally activated processes or by quantum mechanical tunneling. The states of a long junction present a unique opportunity for studying the lifetime of the energy states, in the presence of dissipation.

Usually, thermally activated processes can be described[4] by an Arrhenius law where the transition rate can be written as:

$$\Gamma = \frac{\omega_o}{2\pi} \exp.\ (-V/kT) \qquad (4)$$

where V is the barrier that the particle has to overcome at a temperature T, and $\frac{\omega_o}{2\pi}$ is the number of attempts it makes in trying to escape from the well. At low enough temperatures the rate will become temperature independent as the escape from a well will be by quantum mechanical tunneling. This will occur around a temperature given by

$$T_Q = \frac{\hbar\omega_o}{2\pi k} \qquad (5)$$

where ω_o is a characteristic frequency of the particle in the well. In the quantum limit the tunneling rate out of the well becomes of the form

$$\Gamma = \frac{\omega_o}{2\pi} \left(\frac{864\pi V}{\hbar\omega_o}\right)^{\frac{1}{2}} \exp.^{-}\left(\frac{36V}{5\hbar\omega_o}\right) \qquad (6)$$

It should be noted that in going from one state to the next, the dissipation may be voltage dependent.

To study this we have mounted a long Josephson junction inside a ^3He-^4He dilution refrigerator and the junction was biased at a Fiske step. At some bias this state can become metastable and the particle in it (the junction phase) can tunnel to the next state. This provides a double well where the lifetimes in each well can be adjusted by the current bias. At a certain bias the junction

fluctuates from one state to the next and back down displaying a telegraph noise whose voltage magnitude is the voltage separation between adjacent steps.

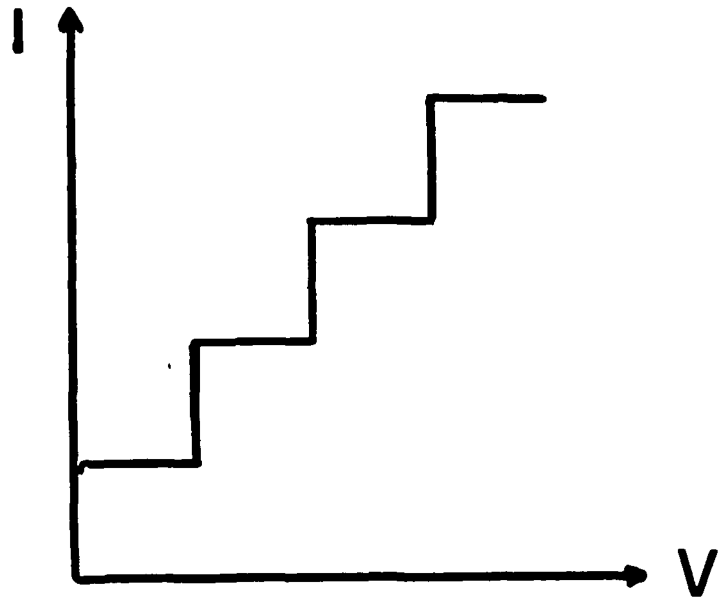
Fig. 1(a) shows the Fiske steps where the lifetime was studied at adjacent steps. As mentioned before, this situation corresponds to a weakly biased double well as shown in Fig. 1(b). The experiments consisted of measuring the lifetime in each well as a function of bias and temperature. Fig. 2 shows a typical result. From this study we obtained the following observations:

- from 2 K to 0.01 K, the lifetime had an exponential temperature dependence.
- the lifetime studies were for 2 voltage states, separated by about 40 μvolts. This is in contrast with other published data where the transitions were studied for $V = 0$ to $V \neq 0$ states. Because the energy separation was small in our experiments, the voltage dependence of the losses did not play such an important role.
- our results are in the temperature range where the mechanism characterizing the lifetime of the states changes from thermal activation to quantum mechanical tunneling.
- barrier attempt rates were found to be in the range of $10^4 - 10^3$ Hz.
- our junction was in very good thermal equilibrium with the thermometer because cooling was maintained by conduction and convection—the sample was inside the mining chamber of the $^3He - ^4He$ dilution refrigerator. The cooling of junctions to such low temperatures is tricky.

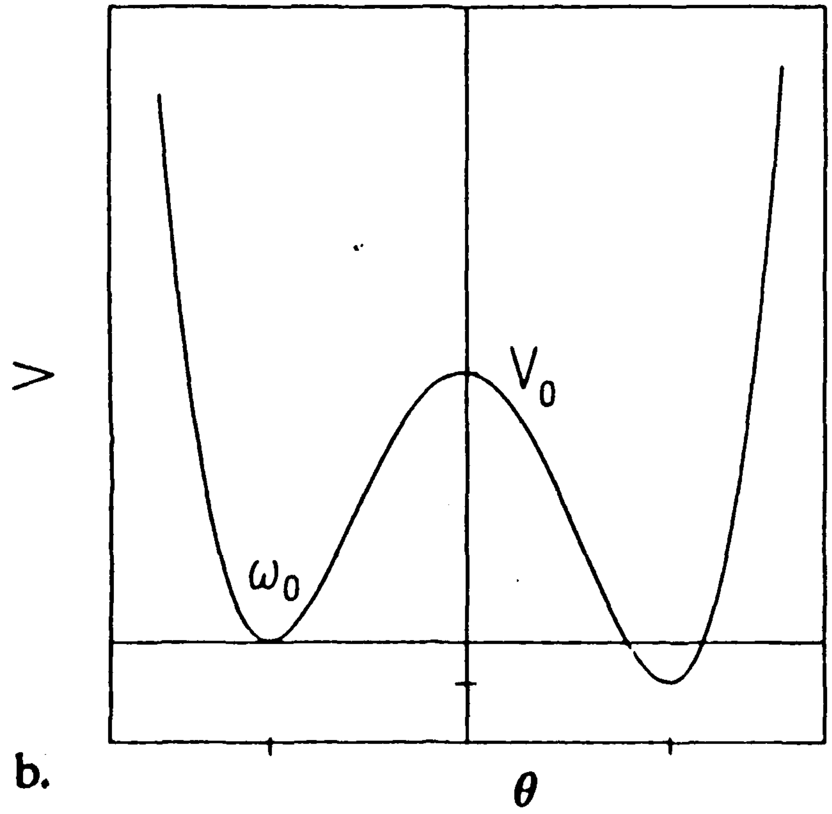
The analysis of our data is based on using the current step height and its dynamic resistance as the basic units for the behavior of the junction. It is equivalent to the critical current of a regular junction and its internal resistance.

The results that were obtained bring out important conclusions for:

- quantum mechanical tunneling and effects of dissipation.
- dynamics of fluxons in long junctions.



a.



b.

Fig. 1(a) Fiske Steps on I-V curve

Fig. 1(b) Double potential well corresponding to adjacent Fiske steps.

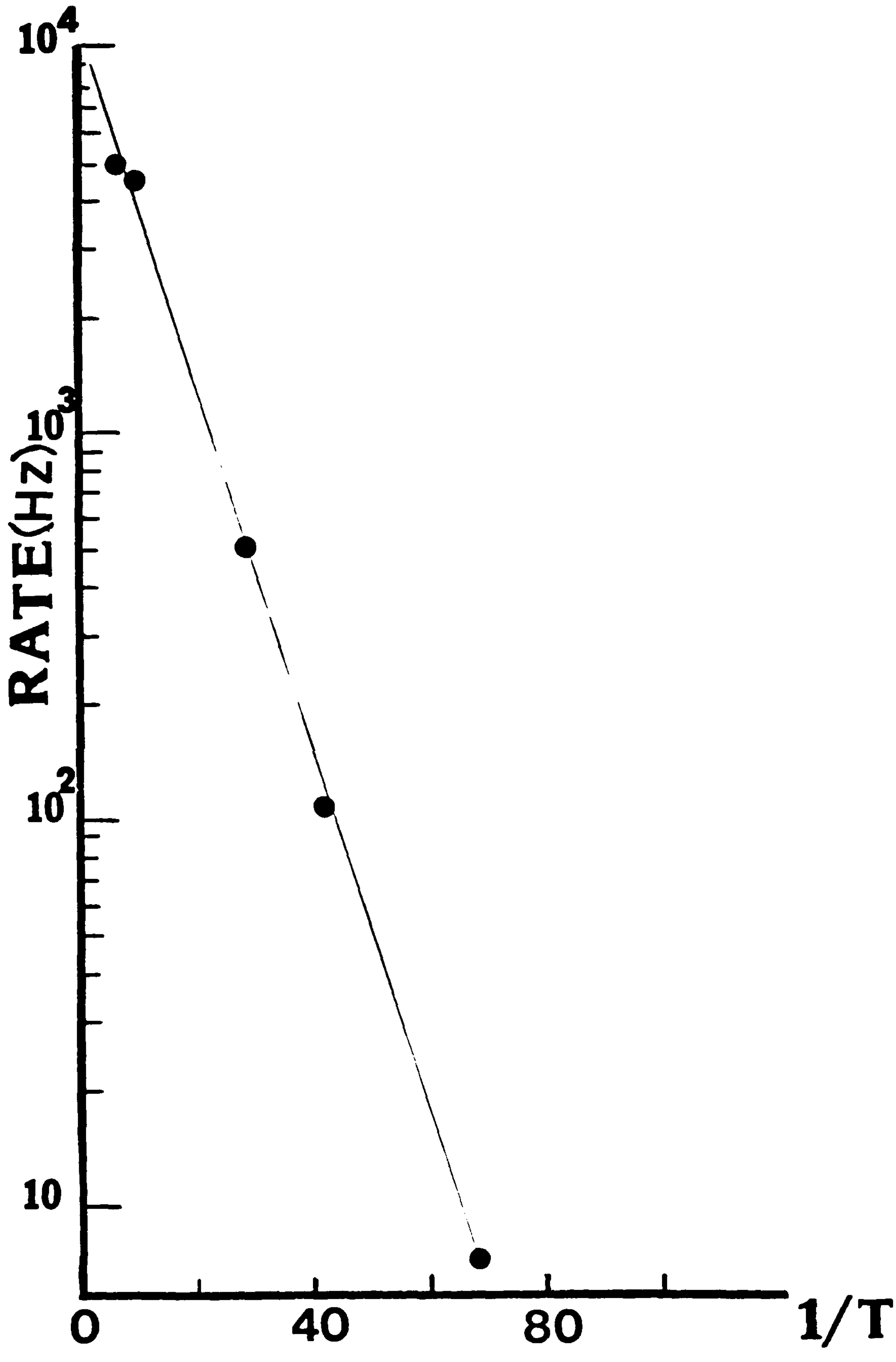


Fig. 2 Tunneling rate between 2 wells as a function of 1/T.

- nucleation of fluxons. This is an interesting aspect useful for applications and to other areas such as magnetism or vapour-liquid transitions[5].

The results are presently being analyzed.

B. High Frequency Oscillator

A long Josephson junction may be regarded as an open-ended section of transmission line having electromagnetic resonances at frequencies

$$f_n = \frac{n\pi v}{L} \tag{7}$$

where v is the phase velocity in the dielectric barrier, L is the junction length, and n is an integer. The non-linear interaction between fluxon motion and the electromagnetic fields excited in the junction cavity leads to Fiske steps in the I-V curve, corresponding to constant voltage current steps when current-biased. These self-induced steps are like Shapiro steps due to external microwave irradiation of a junction. When biased at the current steps, coherent microwave radiation is emitted. The method for achieving this is to apply an external magnetic field which generates fluxons in the junction, and to use a bias current through the junction to exert a Lorentz force on the fluxons. Reflections at the edges lead to radiation. The motion of fluxons is resonant and at each reflection an electromagnetic field is radiated from the junction edge, resulting in a microwave emission at a frequency given by $f = u/2L$, where u is the average fluxon speed ($\sim 10^7$ m/sec).

The emitted radiation is characterized by a very narrow linewidth, about 1 in 10^7 of the emitted radiation; this linewidth is determined by the thermal fluctuations of the fluxon speed. It is interesting to estimate the transmission from such an oscillator. When coupled to an external transmission line with characteristic impedance Z, the transmission coefficient between that line and the junction (impedance Z_J) is

$$T = \frac{4Z_J Z}{(Z_J+Z)^2} \tag{8}$$

For free space, $Z \sim 377\ \Omega$, and hence T is about 10^{-4}. Coupling to this device is a problem since Z_J is so low ($\sim 10^{-2}\ \Omega$). To study the emitted radiation, the following experiments were performed:

- self-induced steps in I-V curve.
- coupling to the junction by means of a microstrip line.

The self-induced steps, on the I-V curve, gave information about the resonant frequencies and the Q at the steps, the latter being determined by the dynamic resistance. Indeed the observed steps, in long NbN-Mg-NbN junctions, were sharp, due to small dynamic resistance and hence narrow linewidths were associated with the radiation. For 40 μvolt Fiske steps, typical for $L = 130\ \mu m$ long junctions, the emitted radiation was at $f \approx 20$ GHz. The linewidth at temperature T is given by:

$$\Delta f = (\pi kT/\phi_o^2)(R_D{}^2/R_S) \tag{9}$$

where R_D is the dynamic resistance and R_S the static resistance, and ϕ_o the flux quantum. Previous studies on tunneling and earlier studies on chaos were used to investigate the performance of this oscillator.

An unexpected effect was observed in the NbN long junctions, in that multi-fluxon self-induced steps were present. This is in contrast to our earlier studies of Nb junctions where single-fluxon steps were always observed. The reason for this difference lies in the penetration depth for the two materials; otherwise the junctions were geometrically the same. For Nb, the penetration depth is ~450 Å while for NbN it is between 2500 Å and 5000 Å. Because our electrodes were 3000 Å thick only, flux could enter the junction at many places thus leading to multi-fluxon states. This caused giant resonances as shown in Fig. 3. Such steps correspond to 5-10 fluxons. It is interesting to note the sharpness of the steps. Because of the larger number of fluxons involved, the output radiation power level is expected to be high. Indeed the large current steps show that this is the case.

The multi-fluxon steps can be used for high level oscillators (instead of using[6] arrays!).

In the external coupling method, we have designed masks to fabricate a device where the long Josephson junction oscillator will be coupled by means of

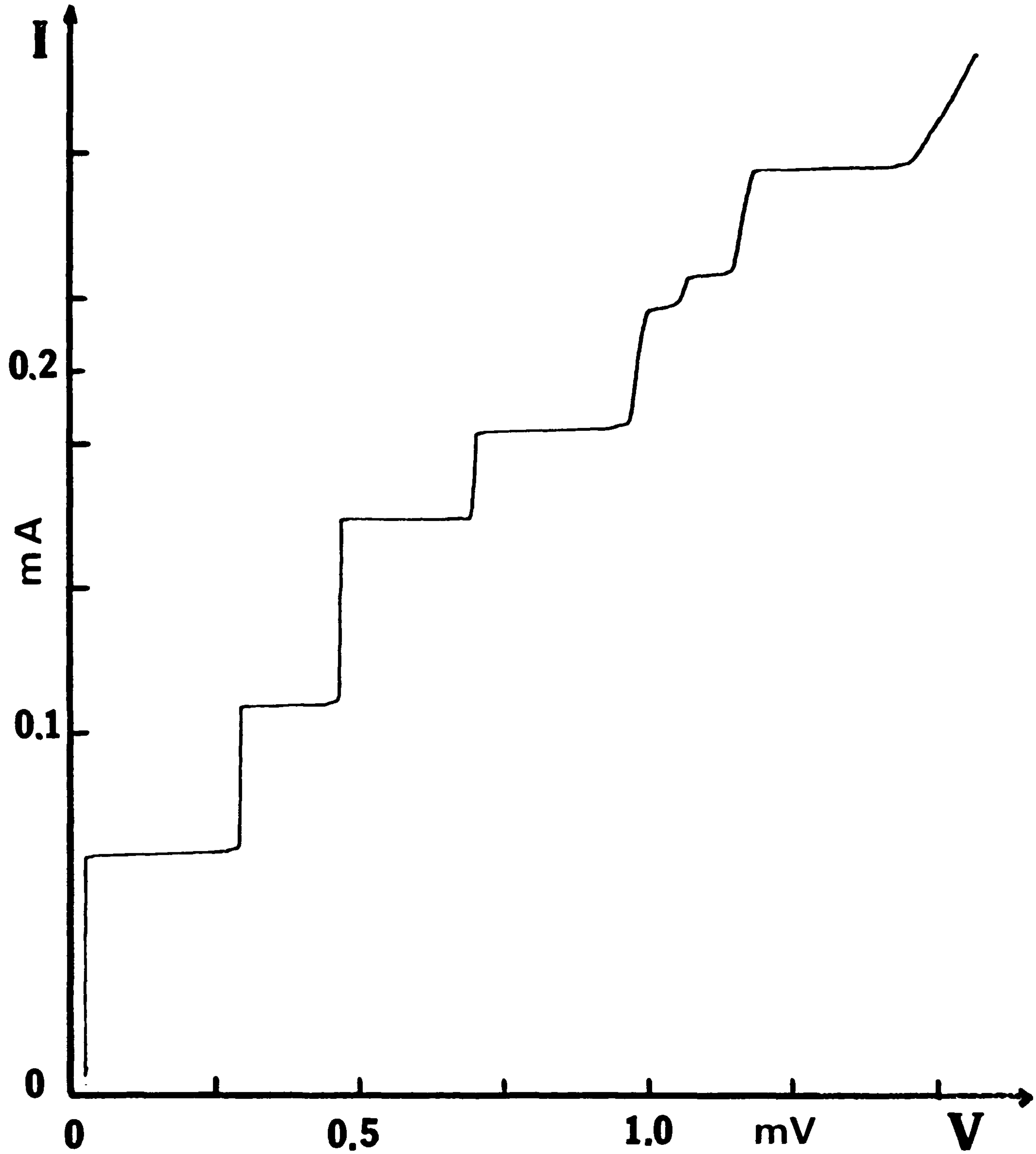


Fig. 3 Multi-fluxon resonances on I-V curve for long NbN junction in a magnetic field.

a strip line to a regular small junction detector. It also will be a NbN device.

C. Very Small Junctions

Two types of very small junctions were fabricated:

(i) NbN film, 6000 Å thick, and Niobium wire tip, using wire 0.127 mm diameter.

(ii) NbN film, 6000 Å thick, and NbN tip using Nb wire, 0.127 mm diameter. The tip was fabricated by reactive sputtering.

The spacing for the above junctions was controlled by means of an STM device, fabricated for the experiments presented here. Fig. 4 shows the experimental details; this apparatus has been used at room temperatures, liquid nitrogen temperature and liquid helium temperature. The tip translator is a piezoelectric tube, PZT-5H made by Staveley NDT Technologies, Inc., EBL Company. Details of this apparatus are described in the Master's Thesis of Ruiyong Li[7].

The results obtained with this device are:

- superconducting energy gap at 4 K for Nb - Nb = 2.9 mvolts.
- superconducting energy gap at 4 K for NbN - NbN = 5.0 mvolts.
- Coulomb blockade at 4 K. A typical value for the blockade voltage, e/2C, is 75 millivolts. This corresponds to a capacitance C of 1.04×10^{-18} Farad. This is shown in Fig. 5.
- Coulomb staircase for NbN - NbN capacitor at 4 K. The temperature was also lowered to 2 K. Fig. 6 shows the results of a staircase at 4 K. The voltage steps decrease as the tip is brought closer to the substrate, indicating that the capacitance is being changed. Fig. 7 shows another set of Coulomb staircase in the I-V curve; the top trace shows the derivative (poorly done!). Fig. 8 shows similar results.
- at some position of the tip the voltage step around zero bias (the first step) changes from a voltage spacing of e/C to 2e/C.
- Coulomb staircase for NbN - NbN capacitor is seen even at 77 K. This is shown in Fig. 9. The results are in agreement with the requirements of equation 1.

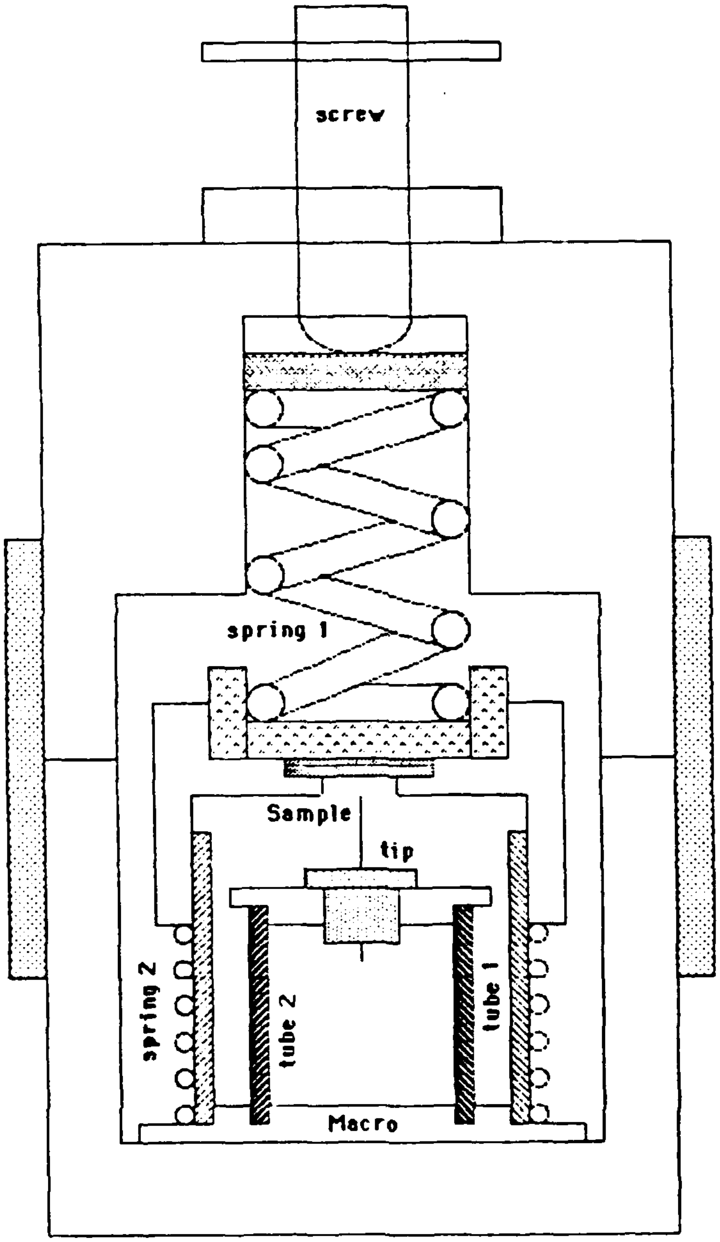
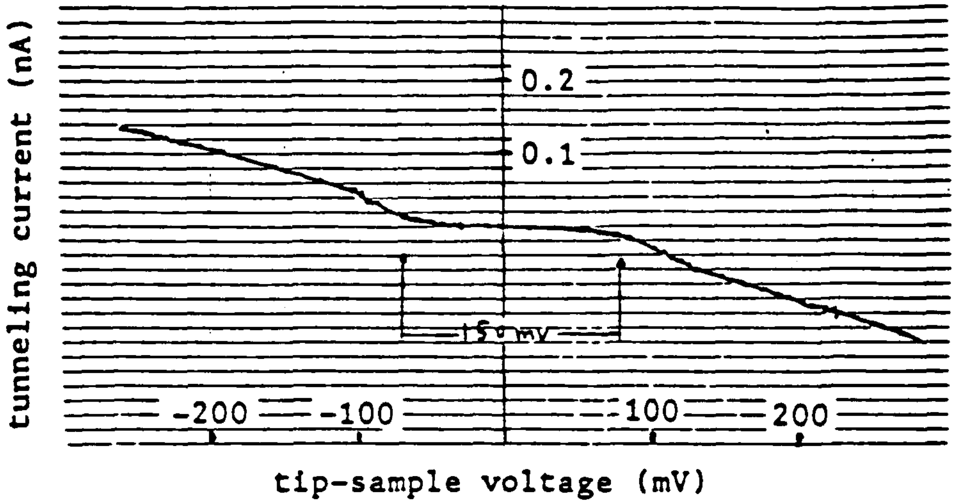
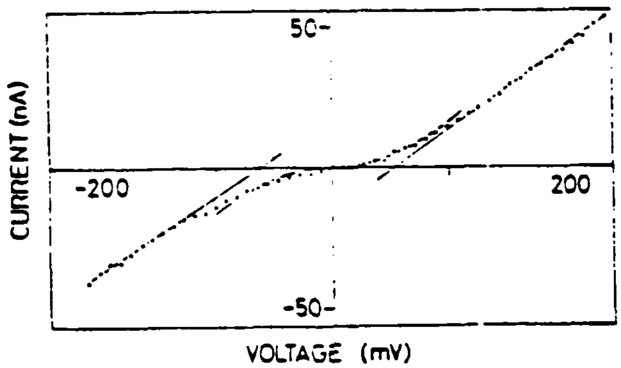


Fig. 4 Experimental set-up of STM.



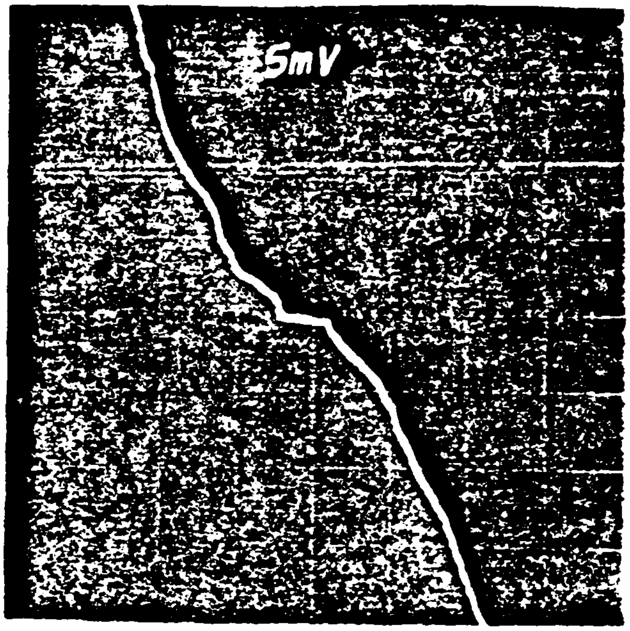
a. Measured Coulomb blockade in NbN/NbN



b. By courtesy of P.J.M. van Bentum etal, presented here as a comparison.

Fig. 5 Coulomb blockade for Nb - NbN tunnel junction and a comparison with published data.

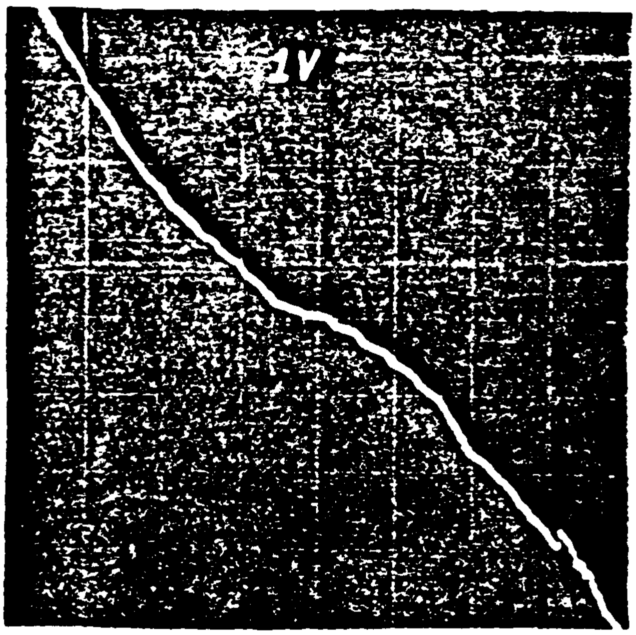
Tunneling current (5nA/cm)



(a) step width 61 mV.

Tip-sample voltage (100mV/cm)

Tunneling current(10nA/cm)



(b) step width 35 mV.

Tip-sample voltage (100mV/cm)

Fig. 6 I-V curve for NbN - NbN junction showing Coulomb staircase.

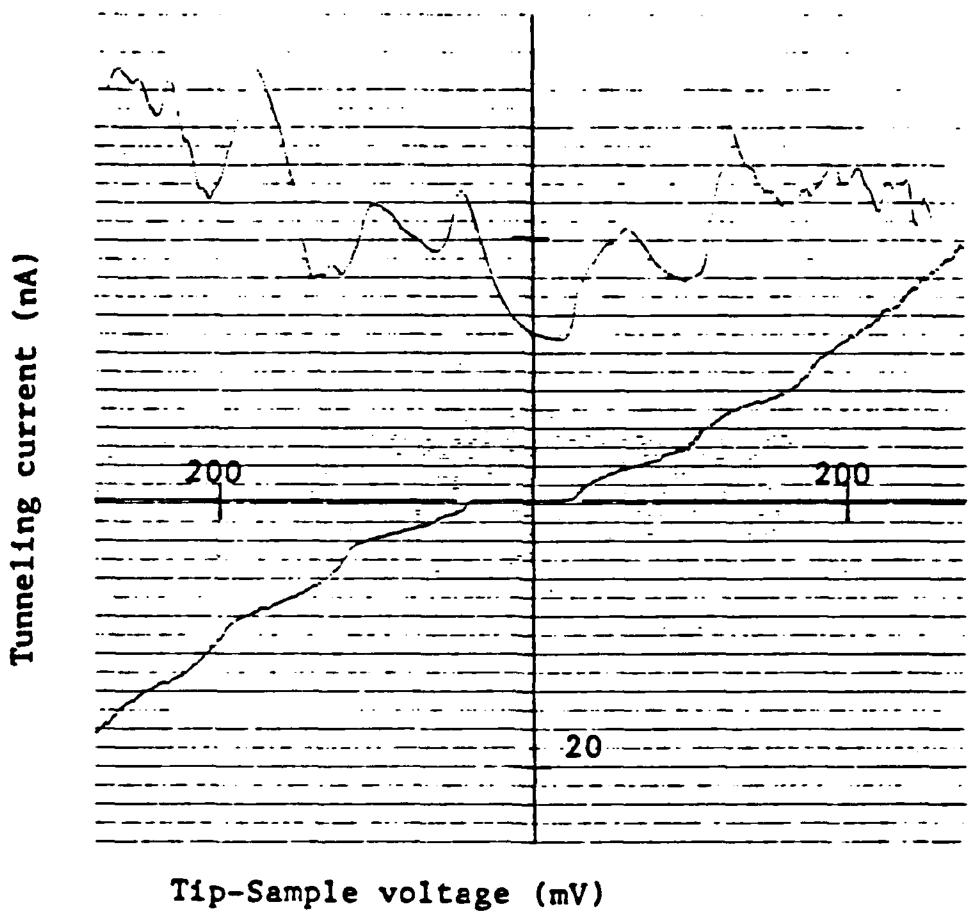


Fig. 7 I-V curve and dI/dV - V curve for NbN - NbN junction showing Coulomb staircase.

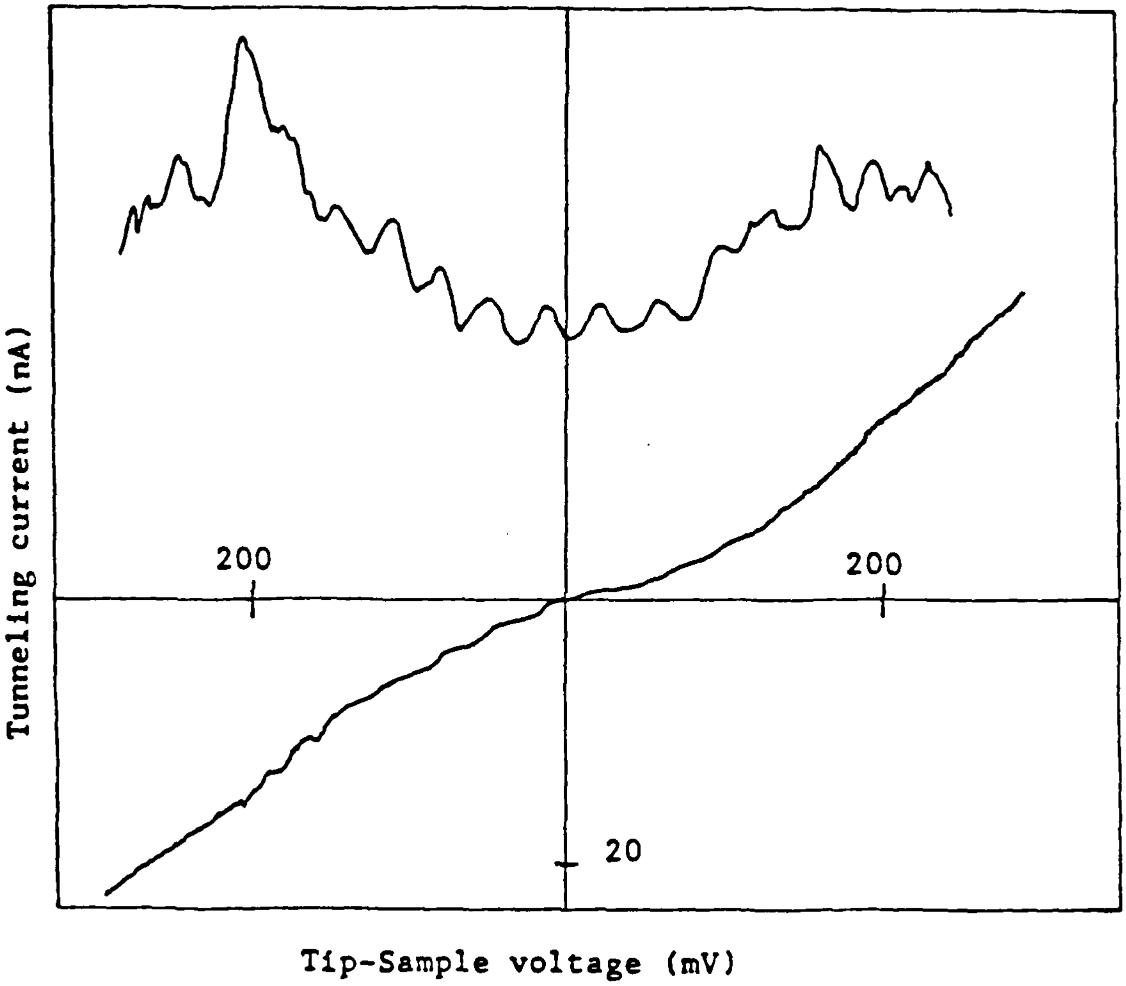


Fig. 8 I-V curve and dI/dV - V curve for NbN - NbN junction at a different tip-substrate spacing.

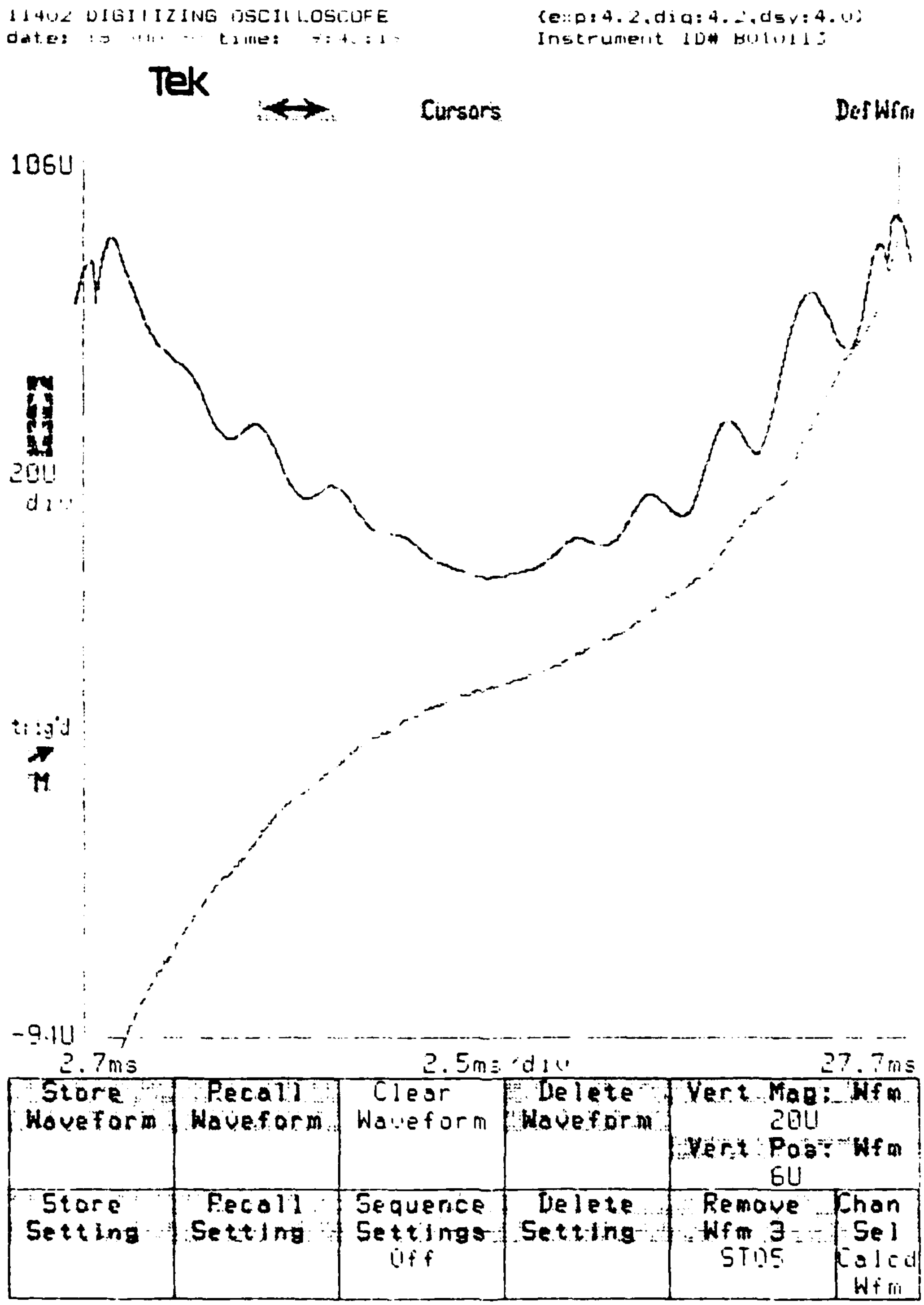


Fig. 9 Coulomb staircase for NbN - NbN junction at 77 K.

We have shown that very small junctions can be fabricated and we are ready to study Bloch oscillations. Single electron behavior will be easier to see than Cooper pairs because single electrons are localized and Cooper pairs are spread out.

The results presented above are very interesting but they also present many questions about the physics involved. Some of the questions are:

- is the junction current or voltage biased?
- why is there a Coulomb staircase?
- with a capacitance as small as 10^{-18} Farad, how can one measure single electron effects?
- is it possible that our capacitor, which consists of a tip and a substrate, is really two capacitors in series? This could happen if there were a loose particle between the tip and the substrate. Such a model has been used by other groups to explain their results[8,9]. The situation, however, may be more complicated than that.

D. New Applications

In doing the proposed research we have paid close attention to possible applications of superconductivity. The following applications have resulted from this research:

(i) Analog to Digital Converter.

Method:
- use long Josephson junction
- create fluxons by applying an external magnetic field from a control line
- ramp the signal to be converted through the long Josephson junction. This leads to a series of Fiske steps, displaying current steps at fixed voltages
- differentiate this signal to get pulses for every level of quantization.

This unit works as a quantizer and converter. Fig. 10 shows the preliminary results for a sine wave at 500 Hz being quantized and then digitized by a high pass filter.

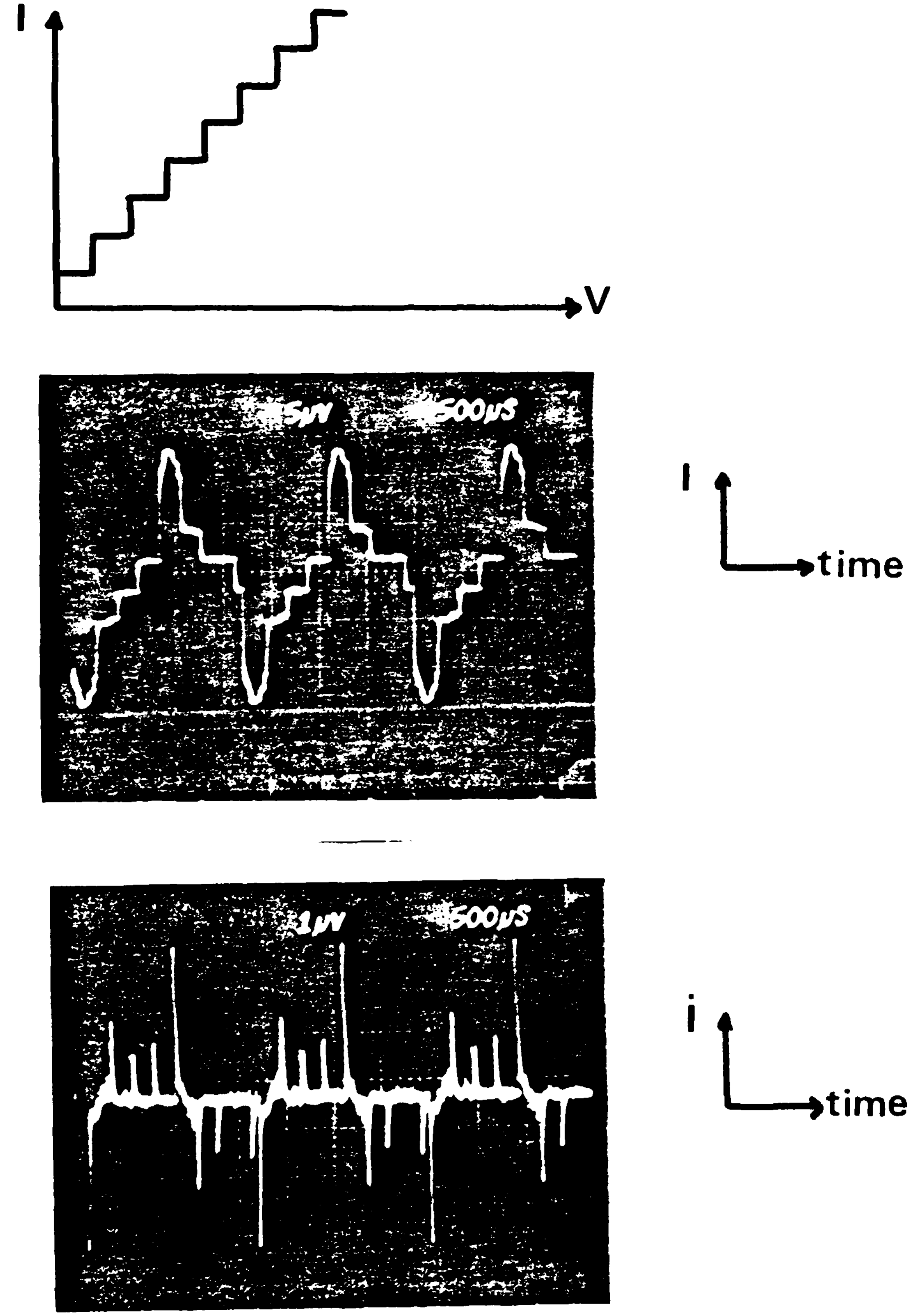


Fig. 10 Principle of A-D conversion using long NbN Josephson junction.

(ii) High Frequency Oscillator

High frequency oscillators based on fluxon motion in long Josephson junctions have been studied by various groups. As a result of our studies of fluxon motion in junctions, we have observed multi-fluxon behavior which leads to giant Fiske steps. The steps are remarkably sharp, i.e. small dynamic resistance, and hence the linewidth is narrow. Moreover, large amounts of power are expected to be radiated by these junctions when biased at the voltage steps. We believe that multi-fluxon effects are caused by the penetration of magnetic field along the junction, rather than at the edges, and it is due to the electrode thickness being less than the Josephson penetration depth. Similar results have been reported[10] recently for junctions where artificial traps have been introduced during the junction fabrication. This may not be necessary as demonstrated in our results. Also, our approach produces much sharper resonances.

3. EXPERIMENTS FOR NEXT PERIOD

We propose a continuation of the experiments just described with emphasis on:

- coupling microwaves from long Josephson junctions to very small junctions
- looking for Bloch oscillations
- studying characteristics of fluxon oscillators
- investigating the application of small junctions to A-D converter
- studying quantum mechanical tunneling in long junctions at temperatures below 1 K and investigating effects of damping.

4. Publications and Presentations

- "Period Doubling in a Perturbed Sine-Gordon System, a Long Josephson Junction", D.J. Zheng, O.G. Symko, and W.J. Yeh, Phys. Let. A 140, 225 (1989).

- "Temperature Dependent Fluxon Fluctuations in Long Josephson Junctions", B.S. Han, B. Lee, O.G. Symko, and D.J. Zheng, to be published in J. of Low Temp. Physics.
- "Chaos in Long Josephson Junctions Without External RF Driving Force", W.J. Yeh, O.G. Symko, and D.J. Zheng, Phys. Rev. B 42, 1990.
- "Substeps in the First Fiske Step Mode of Long Josephson Junctions", W.J. Yeh, O.G. Symko, and D.J. Zheng, in preparation for Phys. Letters A.
- "Fluxon Tunneling in Long Josephson Junctions in a Magnetic Field", L. Baselgia, O.G. Symko, and W.J. Yeh, in preparation.

"Fluctuations in Fluxon Transitions in a Long Josephson Junction at Very Low Temperatures", L. Baselgia, O.G. Symko, W.J. Yeh, and D.J. Zheng, Oral Presentation at Amer. Phys. Soc. 1990 March Meeting, 35, no. 3, 477 (1990).

"Low Temperature Scanning Tunneling Microscope and its Application to Studies of Small Josephson Junctions", Ruiyong Li, Master of Science Thesis, Department of Physics, University of Utah, June 1990.

- Patent applications are in preparation for the new applications.

5. PERSONNEL

Ludi Baselgia, Graduate Student for Ph.D. She is working on fluctuations and tunneling in long Josephson junctions.

Ruiyong Li, Graduate Student for Ph.D. He is working on very small junctions.

Mark Reeve, Graduate Student for Ph.D. He is working on the long Josephson junction oscillator.

Wei-Jiang Yeh, Visiting Research Physicist. He left in May 1990 for a faculty appointment as Associate Professor at the University of Idaho, Moscow, Idaho.

J. Gold, undergraduate assistant.

M. Hurben, undergraduate assistant.

Orest G. Symko, Principal Investigator.

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